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Disk mass accretion rate and infrared flares in GRS 1915+105

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Abstract. We have analyzed in detail a set of Rossi X-ray Timing Explorer (RXTE) observations of the galactic microquasar GRS 1915+105 corresponding to times when quasi-periodic oscillations in the infrared have been reported. From time-resolved spectral analysis, we have estimated the mass accretion rate through the (variable) inner edge of the accretion disk. We compare this accretion rate to an estimate of the mass/energy outflow rate in the jet. We discuss the possible implications of these results in terms of disk-instability and jet ejection, and in particular note an apparent anti-correlation between the accretion and ejection rates, implying that the gas expelled in the jet must leave the accretion disk before reaching its innermost radius.

Key words: accretion, accretion disks – binaries: close – X-rays: stars – stars: individual GRS 1915+105

1. Introduction

GRS 1915+105 is a transient X-ray source discovered in 1992 with WATCH (Castro-Tirado, Brandt & Lund 1992). Since then it has probably never switched off completely and it has remained as a highly variable bright X-ray source (see Sazonov et al. 1994; Paciesas et al. 1996; Bradt et al. 2000). It is the first Galactic object that was found to show superluminal expansion in the radio (Mirabel & Rodríguez 1994). The interpretation of this phenomenon in terms of relativistic jets (Rees 1966) implies bulk velocities of the ejecta of $\geq 0.9c$ at an angle of 60–70 degrees to the line of sight (Mirabel & Rodríguez 1994, Fender et al. 1999, Rodríguez & Mirabel 1999). Because of the high value of the extinction on the line of sight, no optical counterpart is available, but an infrared counterpart has been found (Mirabel et al. 1994). The source is suspected to host a black hole because of its high X-ray luminosity and its similarity with another Galactic superluminal source GRO J1655-40 (Zhang et al. 1994), for which a dynamical estimate of the mass is available (Orosz & Bailyn 1997).

Four years of monitoring with the All-Sky Monitor (ASM) on board RXTE showed that the 2-10 keV flux of GRS 1915+105 is extremely variable, considerably more than any other known X-ray source (see Bradt et al. 2000). See Belloni et al. (2000) for a complete reference list of RXTE observations of the source.

Belloni et al. (1997a,b), from the analysis of selected X-ray spectra, showed that the X-ray variability of the source can be interpreted as the repeated appearance/disappearance of the inner portion of the accretion disk, caused by a thermal-viscous instability. During the low-flux intervals, when the source spectrum hardens considerably, the inner disk up to a certain radius becomes unobservable and is slowly re-filled again. A more complete picture of these variations, where the observations were classified into twelve different classes and another type of (soft) low-flux intervals was presented, was shown by Belloni et al. (2000). Additional spectral analysis has been presented by Markwardt et al. (1999) and Muno et al. (1999), who analyzed in detail the connection between QPOs and energy spectra in GRS 1915+105. One of the problems caused by the exceptional variability of the source is that it is difficult to estimate the accretion rate through the disk or even to rate observations according to accretion rate.

Quasi-periodic variability in the radio, infrared and millimetre bands has been discovered (Pooley 1995, Pooley & Fender 1997; Fender et al. 1997; Fender & Pooley 2000). Fender et al. (1997) suggested that these oscillations could correspond to small ejections of material from the system. Indeed, these oscillations have been found to correlate with the disk-instability as observed in the X-ray band (Pooley & Fender 1997; Eikenberry et al. 1998,2000; Mirabel et al. 1998). This suggests that (some of) the gas is ejected from the inner disk during each low-flux interval. On longer time scales an analogous pattern is observed in the form of major relativistic ejections occurring at the end of a 20-day X-ray dip or 'plateau' (Fender et al. 1999).

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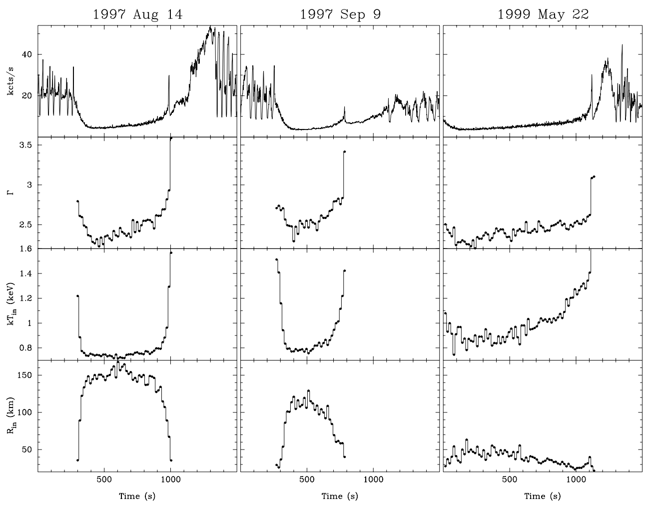

Fig. 1. PCA light curves and corresponding timing evolution of selected spectral parameters (power-law photon index Γ, inner disk temperature kT_{in} and radius R_{in}) from the three observations for which detailed analysis was possible (see text). Light curves have a 1s time resolution, parameters are from 16s bins. The parameters are shown only for the state C intervals (see Belloni et al. 2000).

In this Letter we present the results of detailed time-resolved spectral analysis of RXTE/PCA data of observations when (quasi-)simultaneous infrared data are available. We estimate the value of the accretion rate through the disk for each observation and show that it is anticorrelated with the estimated jet power.

2. Data analysis

The published infrared observations of GRS 1915+105 for which there are simultaneous or quasi-simultaneous (ie. within 2 days) RXTE/PCA data are those from Mirabel et al. (1998), Eikenberry et al. (1998), Fender et al. (1998), Eikenberry et al. (2000), Fender & Pooley, (2000). All observations reveal very variable X-ray light curves (see Table 1), corresponding to classes β, ν and θ in the classification by Belloni et al. (2000).

For each observation, we produce light curves at 1s time resolution (from `Standard1` data) and isolated the long hard low-flux intervals corresponding to state C (unobservable inner disk) of Belloni et al. (2000). For each interval, we measured its length from the light curve (see Table 1). Then we accumulated spectra on a time scale of 16 seconds from `Standard2` data, thus retaining the full energy resolution and coverage of the PCA. From each spectrum, we subtracted the background estimated with `pcabackest` vers. 2.1b. We did not correct for deadtime effects, but we do not expect this effect to be too important. For each observation in PCA epoch 3 we produced a detector response matrix using `pcarsp`, while for epoch 4 we used the response provided on line by K. Yahoda [1]. We fitted each spectrum with the "standard" model used for black-hole candidates, consisting of the superposition of a multicolor disk-blackbody and a power law. By assuming a distance of 12.5 kpc and a disk inclination of 70° (Mirabel & Rodríguez 1994), we can derive from the fits the inner radius of the accretion disk. Correction for interstellar absorption (fixed to 6×10^{22}cm^{-2}, see Belloni et al. 2000) and an additional emission line (fixed at 6.4 keV) were also included. A systematic error of 1% was added. The value of the reduced χ^2 was usually around 1, although some fits were slightly worse. The resulting interesting parameters (inner disk radius and temperature, slope of the power law) as a function of time are shown in Fig. 1 for three of the five observations, for which this automated procedure gave good results. The remaining two observations had to be treated more carefully. The observation from 1997 Sep 15th, the only one from class θ, resulted in an extremely strong power law component, with a photon index steeper than 3. The softness and intensity of this component made it impossible to obtain sensible values for the disk parameters, although there is evidence of its presence. This enhanced power law is probably the reason of the difference between this class and the others (see Belloni et al. 2000). The observation from 1998 July 10th did not include full state-C intervals: in this case, we measured the length of the intervals from the infrared (Eikenberry et al. 2000). Also, the inner disk radius resulted to be larger and therefore more difficult to measure as this component is softer. In order to estimate the disk parameters, we produced a 32s spectrum corresponding to the bottom of the dip only and obtained the best fit parameters, corresponding to the largest inner radius. This is the reason why there is only one point for this observation in Fig. 2.

3. Results

In principle, from each spectrum the accretion rate through the measured inner radius of the disk could be measured from the values of kT_{in} and R_{in} (see Belloni et al. 1997a) by using the expression from a standard thin accretion disk. However, given the errors on these parameters, this measurement is too uncertain. In order to obtain an improved estimate of the disk accretion rate or, better, a ranking of the observations in terms of accretion rate (since the actual values of the inner disk radii obtained with the multicolor disk-blackbody model are probably underestimates, see Merloni, Fabian & Ross 1999), we plotted the values corresponding to the deepest parts of the X-ray light curves in a kT_{in} vs. R_{in} plane (see Fig. 2). If for each observation the disk accretion rate was constant, the points should lie on the diagonal lines corresponding to a slope $-3/4$ (as, for a given $\dot{M}$, $T \propto R^{-3/4}$ – Belloni et al.

[1] `http://lheawww.gsfc.nasa.gov/users/keith/epoch4/`

Table 1. Log of PCA observations and summary of spectral parameters (see text). Classes in column 3 correspond to the classification from Belloni et al. (2000).

Date	Obs#	Class	T_{start}(UT)	Δ t (s)	R_{max}(km)	$\dot{M}_{disk}$ ($M_\odot$/yr)	$\dot{M}_J$ ($M_\odot$/yr)	P_J (erg s^{-1})
14/8/97	20186-03-03-01	β	4:02	530-690	170± 14	1.3×10^{-7}	6×10^{-7}(a)	9×10^{37}
09/9/97	20402-01-45-03	β	6:00	500-720	128± 13	7.1×10^{-8}	3×10^{-7}(b)	1×10^{38}
15/9/97	20186-03-02-00	θ	12:31	600-1000	—[c]	—[c]	5×10^{-7}(d*)	9×10^{37}
10/7/98	30182-01-03-00	ν	5:05	2250-3500[e]	288± 27	2.7×10^{-7}	10^{-7}(f)	4×10^{37}
22/5/99	40702-01-02-00	ν	20:41	1100-1370	55± 13	8.0×10^{-9}	2×10^{-6}(g*)	3×10^{38}

[a] from Eikenberry et al. (1998); [b] from Mirabel et al. (1998); [c] not measurable; [d] from Fender & Pooley (1998)
[e] determined from IR data; [f] from Eikenberry et al. (2000); [g] from Fender & Pooley (2000); * quasi-simultaneous

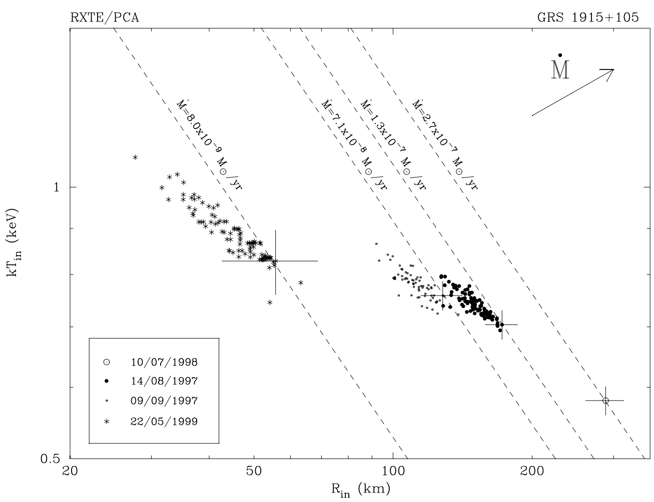

Fig. 2. Evolution of temperature at the inner disk radius versus inner disk radius for the four observations for which a reliable estimate could be obtained (see text). Only the low-flux sections of the data from Fig.1 are shown. Typical errors are shown for each observation. The dashed lines correspond to different values of disk accretion rate according to the thin disk model.

1997a). Their actual distribution is flatter, showing that there is a deviation from the expected law, but it is interesting to note that the distributions lie on parallel curves in the log-log plane. This indicates different values of the disk accretion rate. Lines corresponding to the larger measured radius for each of the four observations are shown in Fig. 2 with their associated accretion rate value. Typical 1σ errors are also shown. Although the actual values for the accretion rate are probably not accurate, on the basis of this plot we can rank the observations by accretion rate. It is important to note that the accretion rate measured this way correspond to matter passing *through* the observed inner radius of the disk only: if some matter leaves the disk before that radius, its presence cannot be detected with this procedure. This estimate of accretion rate can be double checked by considering the length of the state C intervals, which Belloni et al. (1997a,b) interpreted as the viscous time scale of the disk at the edge of the unobservable region which is refilled. The observation from 1999 May 22nd has a smaller inner disk radius (see Fig. 2) than the 1997 ones and a longer re-fill time (Tab. 1), indicating a lower value of the accretion rate. The 1998 July 10th observation has a much larger inner disk radius than the 1997 ones, by a factor of 1.7 and 2.3, which would correspond to a re-fill time longer by a factor 6.4 and 18 respectively, while it is much shorter, indicating a higher accretion rate.

4. Discussion

The results of our analysis indicate that, at least for observations of class ν and β (which have many similar traits), we have a way to estimate the disk accretion rate during an instability event, when the inner disk radius grows from its "minimum" value of $\sim$30 km and slowly moves back to it. Although we know that the measured value is only an underestimate, it is natural to associate this minimum value with the innermost stable orbit. It is interesting to compare these values, or at least their ranking, with the rate of ejection in the jets. As we mentioned above, the accretion rate measured through this procedure is associated to matter flowing *through* the observable inner edge of a geometrically thin accretion disk. Some of the accreting gas must leave the accretion disk to form the jet, unless it is entirely composed of pairs generated by photon-photon interactions. and how this happens is basically unknown. There are two extreme possibilities: either matter ejected in the jet leaves the accretion disk before entering the innermost regions, thus not contributing to our measured disk accretion rate (case 1), or it leaves it after passing through our measured inner disk radius, in which case it is a fraction of the accretion rate we measure (case 2). In case 1, if the fraction of matter in the jet is constant and the total external accretion rate (disk+jet) is variable, we expect a positive correlation between disk accretion rate (from X rays) and disk ejection rate (from the infrared). If the fraction is variable and the total is constant, these quantities should be anticorrelated. In case 2, if the fraction of matter in the jet is constant, we expect a positive correlation, while the constant total is in this case not possible as the total would be what we measure, which is not observed to be constant. If both fraction and total vary, the situation is complicated. Of course, there is a spectrum of intermediate possibilities, where the jet production is connected to the inner region of the disk in a way that would not allow to dissociate the two processes. With the paucity of existing data, we limit ourselves to the extreme cases. Notice that measuring an anti-correlation would be an indication against case 2.

Table 1 also lists an estimate of the mass ejection rate $\dot{M}_{\rm J}$. This is based upon an equipartition calculation for one proton for each electron, negligible kinetic energy associated with the repeated ejection events, and an average over the repetition period of the oscillations. Note that there is a systematic uncertainty in these numbers due to lack of knowledge of the intrinsic electron spectrum which corresponds to the observed flat-spectrum radio–infrared emission. However, unless the spectral form of the distribution changes between observations then the effect is the same for all data sets and the ranking remains the same. Of course we may be observing synchrotron emission from a pair plasma with no baryonic content, in which case the amount of power being supplied to the jet, $P_{\rm J}$, makes more useful comparison with the accretion rate; this value is also listed in Table 1. For more details of how these quantities are calculated, see Fender & Pooley (2000). Either way, there appears to be an *anticorrelation* between accretion rate inferred from the X-ray spectral fits and the outflow rate of mass/energy in the jet. The low number of points in our sample prevents us from saying something more firm. Notice that an anticorrelation is also suggested by the strong flat-spectrum radio emission observed during long 'plateau' intervals; periods when Belloni et al. (2000) estimate that the accretion rate must be very low. We also note that the faint infrared flares reported by Eikenberry et al. (2000) do not appear to be different from the others in other respects, as the X-ray light curves are too undersampled to allow a detailed correlation.

If future observations show that disk accretion rate and jet ejection rate are indeed anti-correlated, the following scenario could be speculated. A fraction of the accreting gas leaves the geometrically thin accretion disk before reaching the inner edge (from which it would fall into the black hole) and goes into a hot corona. The details are not known, but our results indicate that this does not happen after the inner edge. As the disk refills, the inner radius moves inwards, more soft photons from the disk reach the corona, which causes its Comptonization emission to soften gradually. At the end of the instability period, when the disk is refilled down to the innermost stable orbit, this "reservoir" of hot gas is expelled to produce the jet, resulting in the observed infrared / mm / radio emission, causing the power-law component to steepen dramatically and to cause the sudden change in the X-ray count rate and spectral parameters. Notice that, as we remarked earlier, the distributions of points in Fig. 2 are flatter than the expected curve for a constant disk accretion rate according to a standard thin disk: in other words, as the inner disk radius decreases, the disk accretion rate seems to decrease as well. This could mean that the process that re-routes some gas from the disk to the corona becomes more efficient closer to the central object, and therefore the fraction of matter going into the corona increases as the disk refills.

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